NASA/TM-1999-209684

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October 1999

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Space Administration

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Acknowledgments

This work was conducted under Cooperative Agreements NCCW-68 and NCC1-238. For that portion of the work that was conducted in Russia, the principal investigators were Academician Joseph Fridlyander from the All-Russia Institute of Aviation Metals (VIAM) and Professor Valentin Davydov from the All-Russia Institute of Light Alloys (VILS).

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Evaluation of Pressurization Fatigue Life of 1441 Al-Li Fuselage Panel

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Summary

A study was conducted to evaluate the pressurization fatigue life of fuselage panels with skins fabricated from 1441 Al-Li, an attractive new Russian alloy. The study indicated that 1441 Al-Li has several advantages over conventional aluminum fuselage skin alloy with respect to fatigue behavior. Smooth 1441 Al-Li sheet specimens exhibited a fatigue endurance limit similar to that for 1163 Al (Russian version of 2024 Al) sheet. Notched 1441 Al-Li sheet specimens exhibited greater fatigue strength and longer fatigue life than 1163 Al. In addition, Tu-204 fuselage panels fabricated by Tupolev Design Bureau using Al-Li skin and ring frames with riveted 7000-series aluminum stiffeners had longer pressurization fatigue lives than did panels constructed from conventional aluminum alloys. Taking into account the lower density of this alloy, the results suggest that 1441 Al-Li has the potential to improve fuselage performance while decreasing structural weight.

Symbols and Abbreviations

ε	strain
ν	Poisson's ratio
σ_{hoop}	stress in the circumferential (hoop) direction
σ_{long}	stress in the longitudinal direction
C	circumferential (hoop) direction
E	elastic modulus
k_t	stress concentration factor based on net section stress
L	longitudinal direction (parallel to fuselage centerline)
LaRC	Langley Research Center
LVDT	linearly variable differential transformer
p	pressure
psig	gage pressure above ambient atmospheric pressure in pounds per square inch
r	pressure vessel radius
R	ratio of minimum-to-maximum fatigue load
t	pressure vessel wall thickness
VIAM	All-Russia Institute of Aviation Materials
VILS	All-Russia Institute of Light Alloys

Introduction

The low density and good mechanical properties of Al-Li alloys make them attractive for many structural applications, especially in the aerospace industry (ref. 1). Research and development efforts in Russia and the United States have focused on advanced Al-Li alloys for aerospace applications where reduced structural weight is a critical goal (ref. 2-3). Since 1994, NASA Langley Research Center (LaRC) has engaged in cooperative research activities with the All-Russia Institute of Aviation Metals (VIAM) and the All-Russia Institute of Light Alloys (VILS) in Moscow, Russia, to evaluate a new Russian Al-Li alloy (1441) for fuselage skin applications. The work included cold rolling and heat treatment process development, characterization of microstructure and mechanical properties of cold-rolled sheet, and evaluation of durability of fuselage panels fabricated with 1441 Al-Li skin. This paper focuses on the work conducted at LaRC to evaluate the fatigue behavior of 1441 Al-Li sheet and the pressurization fatigue life of fuselage panels using 1441 Al-Li skin.

Four fuselage panels fabricated by Tupolev Design Bureau under contract to VIAM using 1441 Al-Li were subjected to cyclic pressurization and depressurization to simulate flight conditions. Two panels were tested at LaRC and two were tested at Tupolev. In addition, the S-N fatigue behavior of 1441 Al-Li sheet was evaluated. This report summarizes the results from the tests conducted at LaRC and compares the data with that obtained from VIAM and Tupolev.

Experimental Procedures

Materials

All materials evaluated at LaRC were provided by VIAM. The nominal composition of 1441 Al-Li, in weight percent, is Al - 1.6 Cu - 1.7 Li - 0.95 Mg -0.08 Zr. Sheet fatigue life was evaluated using 0.055-inch thick cold-rolled 1441 Al-Li sheet. The fuselage panels manufactured by Tupolev consisted of 0.055-inch thick 1441 Al-Li skin, 1441 Al-Li ring frames, and V95pchT2 aluminum stiffeners. Alloy V95pchT2 is the Russian version of the U.S. aluminum alloy 7475. All of the 1441 Al-Li was in the T1 condition (annealed at 990°F, water quenched, stretched, aged at 300°F for 24 hours).

Test Specimens

Fatigue specimens

The fatigue life of the 1441 Al-Li sheet material was evaluated using smooth and notched fatigue specimens (see figures 1 and 2). The smooth fatigue specimens ($k_t = 1$) were of the "hour glass" variety with a minimum width of 0.5 inch in the test section. The notched fatigue specimens ($k_t = 2.6$) had a test section that was 1.5 inches in length and 0.5 inch in width with a 0.075-inch diameter hole drilled through the center.

Fuselage pressurization panels

A photograph of one of the two panels that were tested at LaRC is shown in figure 3. The panels, fabricated using the Tupolev-204 fuselage design, were approximately 5 feet long and 5 feet wide with a radius of curvature of 75 inches. Each panel contained two riveted longitudinal single skin overlap splice joints. The two joints had different rivet patterns, as shown in the schematic diagrams in figures 4 and 5. One joint consisted of 3 longitudinal rows of rivets with a 0.8-inch rivet spacing. The other joint consisted of 4 longitudinal rows of rivets with a 1-inch rivet spacing. Nine longitudinal blade stiffeners fabricated from V95pchT2 (7475) aluminum alloy were riveted to each panel. In addition, three ring frames fabricated from 1441 Al-Li alloy were riveted to the panel circumference.

Fatigue Testing

The smooth and notched fatigue specimens were tested at room temperature using a closed-loop servohydraulic fatigue test machine with programmable load profiler. The specimens were tested under constant amplitude loading conditions with an R value of 0.1 at a frequency of 10 Hz. Run-out was defined as 1,000,000 cycles without specimen failure. Fatigue stresses for the notched specimens were calculated based upon the net cross-sectional area.

Panel Pressurization Fatigue Testing

The purpose of the panel pressurization test was to characterize the initiation and growth of fatigue cracks in the riveted joints and to determine the fatigue life of the panels under conditions that simulate fuselage pressurization/depressurization during each flight. The two fuselage panels were tested simultaneously under the same pressure conditions by mounting them in back-to-back fashion to a pressurization test fixture. Due to funding constraints, a simplified test fixture for pressurizing the panels was designed and built using plywood and lumber.

The primary component of the fixture that supported reaction loads from the panel during pressurization consisted of a 0.75-inch thick plywood sheet that was 69.5 inches long by 61 inches wide. Figure 6a shows a schematic diagram of this support structure. A frame of 2-inch by 4-inch lumber was glued and nailed along the perimeter of the plywood sheet. The plywood was stiffened using 2-inch by 4-inch lumber horizontal stiffeners and 4-inch by 4-inch lumber longitudinal stiffeners. The ends of the horizontal stiffeners were beveled to match the contour of the panels to prevent interference when the panels were attached to the fixture. The plywood sheet was perforated to allow equalization of pressure between the panels mounted to both sides of the test fixture. Styrofoam insulation was used to fill up as much internal volume as possible to reduce the time required to pressurize the panels. Figure 6b illustrates the clamping arrangement used to attach the panels to the test fixture. 4-inch by 4-inch lumber was machined to match the contour of the curved fuselage panels. The interior portion of the 4-inch by 4-inch lumber clamp was glued to the frame of the structural support fixture. The panels were mounted to the test fixture using wood screws, with a rubber gasket located between the panels and the clamping fixture. The exterior portion of the clamp was installed using threaded rods that extended through the fixture from front to back along all four sides of the fixture. The clamping force was applied by tightening nuts on the front and back of the fixture. RTV sealant was applied to all edges of the fixture.

Figure 7 shows a photograph of a panel mounted in the pressurization test fixture with instrumentation attached. A second panel is attached to the other side of the test fixture, hidden from view. Pressurization hardware was mounted to the test fixture at the top of the frame. A 50-psig air supply line was attached to the pressurization valve. The valve was interfaced with a microprofiler which controlled the pressure profile. A typical pressure profile is shown in figure 8. The panels were cycled between ambient pressure and 9.4 psig at a rate of approximately 3 cycles per minute. The panels were pressurized from ambient pressure to the target maximum pressure as quickly as possible. When the target maximum pressure was attained, the microprofiler opened the pressure valve to release the pressure as quickly as possible.

The panels were instrumented to measure pressure, strain, and deflection. Pressure was measured by transducers located at the top and bottom of the test fixture. Strain gages were attached to the external surface of both panels in the locations shown in figures 9a, 9b, and 9c. Strain gages 07 and 12 measured strain in the longitudinal direction. The remaining strain gages (01-06, 08-11, 13-15) measured strain in the circumferential direction. In addition, LVDT's were used to measure the maximum panel deflection during the pressurization cycles. The entire assembly was isolated in a closed room for safety purposes. Video cameras were used to monitor both panels. The pressurization testing was interrupted periodically to allow the panels to be inspected for fatigue crack initiation and growth in the riveted joints.

Results and Discussion

Fatigue results

The S-N fatigue behavior of smooth and notched 1441 Al-Li sheet specimens is shown in figure 10. Also shown are reference data from VIAM for 1163 Al (Russian version of U.S. aluminum alloy 2024) alloy sheet. The data for the smooth 1441 Al-Li specimens indicate an endurance limit of approximately 25 ksi at 1,000,000 cycles. This endurance limit compares favorably with that for 1163 Al, which was reported to be approximately 17 ksi at 2,000,000 cycles. The fatigue data for notched specimens show a significantly higher fatigue strength and life for 1441 Al-Li compared to 1163 Al.

Panel pressurization results

The outward deflection of one of the panels during three pressurization cycles is shown in figure 11. This behavior is representative for both panels. During pressurization (loading), the panel deflection varied linearly with pressure to approximately 7 psig, at which point the deflection deviated from linearity. A maximum deflection of approximately 0.4 inch was attained at the peak pressure. During depressurization (unloading), the deflection was highly non-linear, resulting in a hysteresis loop. This hysteresis loop was repeatable.

Figure 12 shows the hoop and longitudinal strain responses in the panel skin measured with strain gage numbers 06 and 07, respectively, over three pressurization cycles. Both the hoop and longitudinal strain varied nonlinearly with pressure. In addition, the longitudinal strain exhibited a relatively large hysteresis during the pressurization cycle, which resembled the shape of the hysteresis loop associated with the panel deflection. The non-linear strain and deflection behavior is believed to be fixture induced. The fixed panel end constraints resulted in the development of bending stresses in the longitudinal direction as the pressure was applied.

Figure 13 shows the hoop and longitudinal stress responses calculated using the strain data from the previous figure and the following biaxial stress equations:

$$\sigma_{hoop} = E\,(\varepsilon_{hoop} + \nu\varepsilon_{long}) \,/\, (1 - \nu^2) \qquad \text{(ref. 4)}$$

$$\sigma_{long} = E\,(\varepsilon_{long} + \nu\varepsilon_{hoop}) \,/\, (1 - \nu^2) \qquad \text{(ref. 4)}$$

where:

E = elastic modulus (11.4 Msi)
ν = Poisson's ratio (0.33)

Also shown in the figure is the hoop stress generated at the maximum pressure (9.4 psig) from the fuselage panels tested at Tupolev. This hoop stress value was provided by VIAM. In addition, the plot shows idealized hoop and longitudinal stress responses to internal pressure for a thin-walled cylindrical pressure vessel (ref. 4). The LaRC fuselage panel hoop stress was approximately 10% less than that for an ideal thin-walled cylinder. The maximum hoop stress applied to the panels tested at Tupolev was within 10% of that applied to the panels at LaRC. The longitudinal stress developed in the panels tested at LaRC was approximately 50% greater than that for an ideal thin-walled cylinder. The test fixture used at Tupolev employed hinges for panel attachment in the hoop direction and flexible seals that allowed the ends of the panel to deflect. This test arrangement reduced the longitudinal stress component in the test panels to minimal levels. Thus, the hoop stresses were similar for the panels tested at LaRC and Tupolev. With respect to the longitudinal stresses, however, the LaRC tests generated stresses that were greater and the Tupolev tests generated stresses that were lower than that for the ideal case.

The pressurization test was interrupted periodically to visually examine the riveted joints in each panel for fatigue cracking. No signs of cracking within the joints were detected by inspections of the exterior of the panels. However, after 193,000 pressurization cycles, one of the panels failed catastrophically along one of the riveted splice joints. Figures 14 and 15 show an exterior view and an interior view, respectively, of the panel after rupture. The fracture occurred in the riveted joint with three rows of rivets. An examination of the panel fracture surface was conducted. Two distinct fatigue cracks were identified, each being approximately 2 inches long. The locations of these fatigue cracks are shown in figure 15. Figure 16 shows a detailed view of one of the fatigue cracks. The fatigue cracks initiated and propagated in the 1441 Al-Li skin along a rivet line hidden from view in the overlap joint, and would only have been detected by dismounting the panels and inspecting the interior of the panels. Thus, the cracks were not observed until fracture occurred. During the panel rupture process, the three ring frames were fractured by overload and the stiffeners buckled. The other panel remained intact, but examination revealed the existence of small fatigue cracks, less than one inch in length, in the riveted joints. These cracks were located in areas similar to the crack locations in the ruptured panel.

The results of the panel pressurization fatigue tests conducted at LaRC and Tupolev are shown in figure 17. Shown for comparison are results provided by VIAM from a Tu-204 fuselage panel constructed using conventional 1163 (2024) aluminum skin. The conventional panel accumulated 163,000 pressurization cycles prior to rupture. The two Al-Li panels tested at Tupolev attained 250,000 cycles without signs of fatigue cracking, at which point the test was stopped. As stated previously, one panel tested at LaRC ruptured after 193,000 pressurization cycles while the other panel remained intact. Testing of the unruptured panel was discontinued because of the difficulties in sealing the back side of the pressure cavity in the back-to-back scheme employed for the pressurization fatigue tests. The data indicate that panels with 1441 Al-Li skin have a longer pressurization fatigue life than do panels with conventional aluminum alloy skin. This result is consistent with the greater fatigue life of 1441 Al-Li sheet compared to 1163 (2024) aluminum sheet. The difference in pressurization fatigue life of the 1441 Al-Li panels tested at LaRC and Tupolev was attributed to the significant longitudinal stresses developed in the LaRC panels as a result of the end constraints.

Conclusions

The results of this study have shown that Russian 1441 Al-Li alloy has several advantages over conventional aluminum fuselage skin alloy with respect to fatigue behavior. Smooth 1441 Al-Li sheet specimens exhibited a fatigue endurance limit similar to that for 1163 aluminum (Russian version of 2024 Al) sheet. Notched 1441 Al-Li sheet specimens exhibited greater fatigue strength and longer fatigue life than 1163 Al. In addition, Tu-204 fuselage panels fabricated by Tupolev Design Bureau using 1441 Al-Li skin and ring frames and V95pchT2 aluminum (Russian version of 7475) stiffeners had longer pressurization fatigue lives than did panels constructed from conventional aluminum alloys. Taking into account the lower density of this alloy, the results suggest that 1441 Al-Li has the potential to improve fuselage performance while decreasing structural weight.

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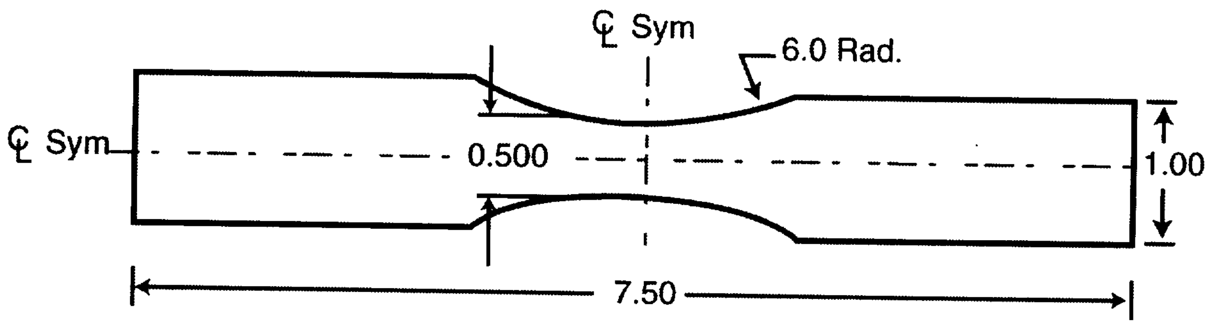

Figure 1. Smooth fatigue specimen ($k_t = 1$). All dimensions are in inches. (thickness = 0.055 inch)

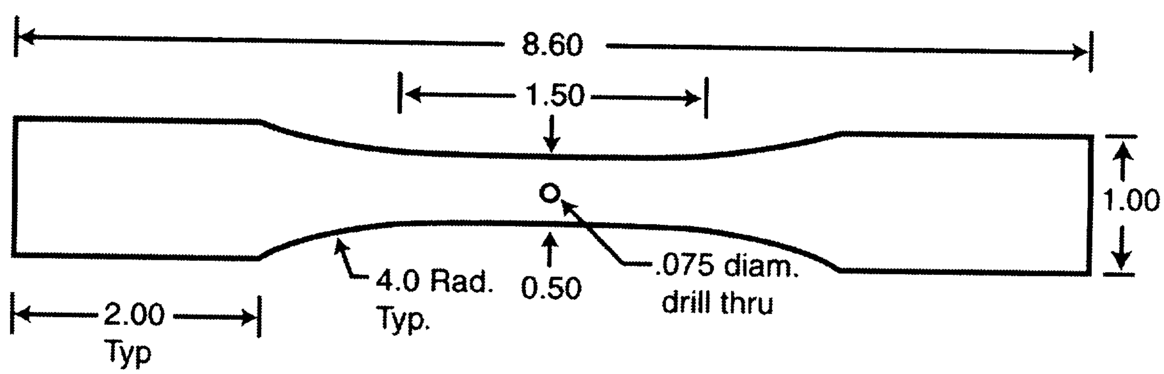

Figure 2. Notched fatigue specimen ($k_t = 2.6$). All dimensions are in inches. (thickness = 0.055 inch)

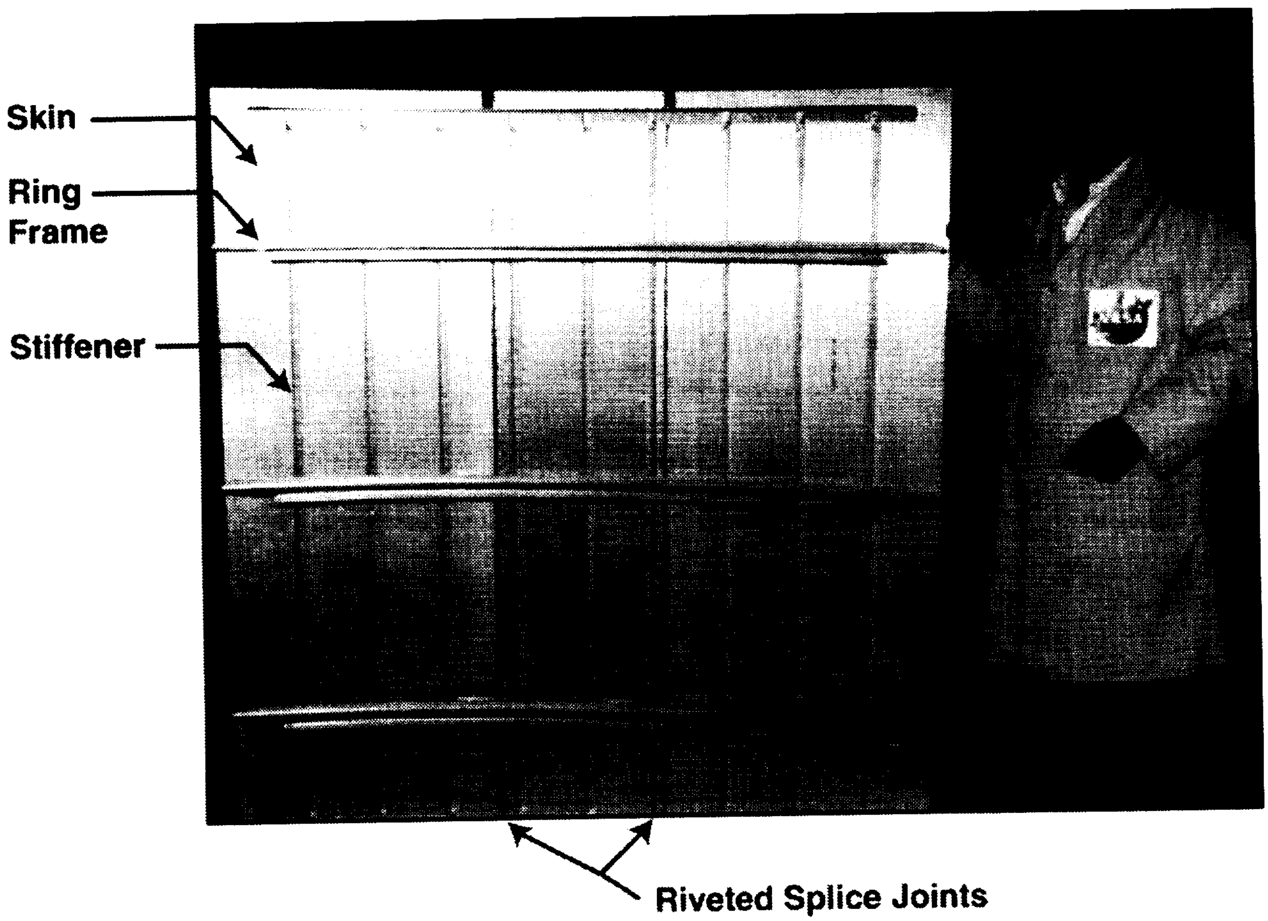

Figure 3. Tu-204 fuselage panel fabricated with 1441 Al-Li skin.

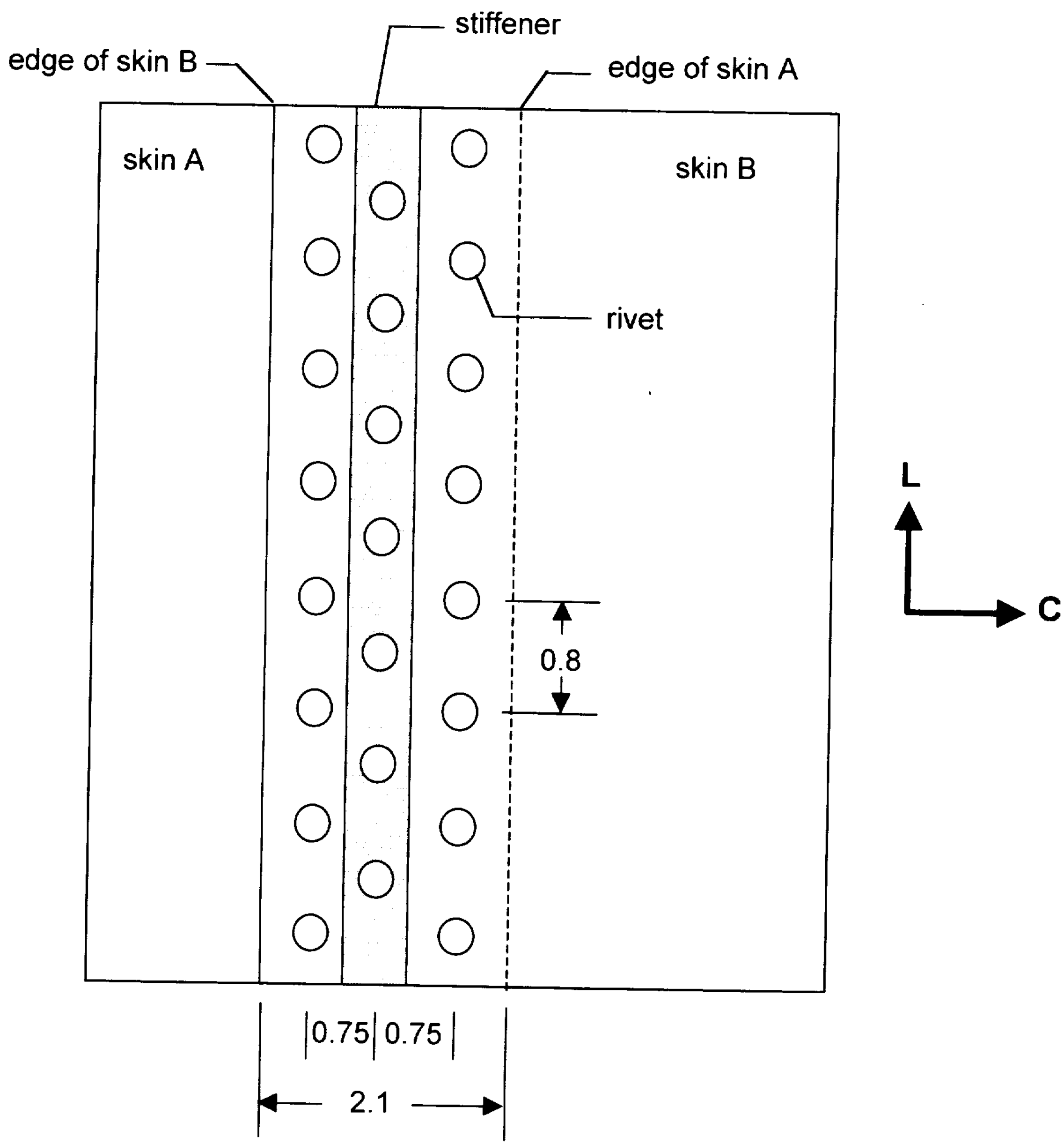

Figure 4. Schematic diagram of riveted splice joint with three rows of rivets. All dimensions are in inches.

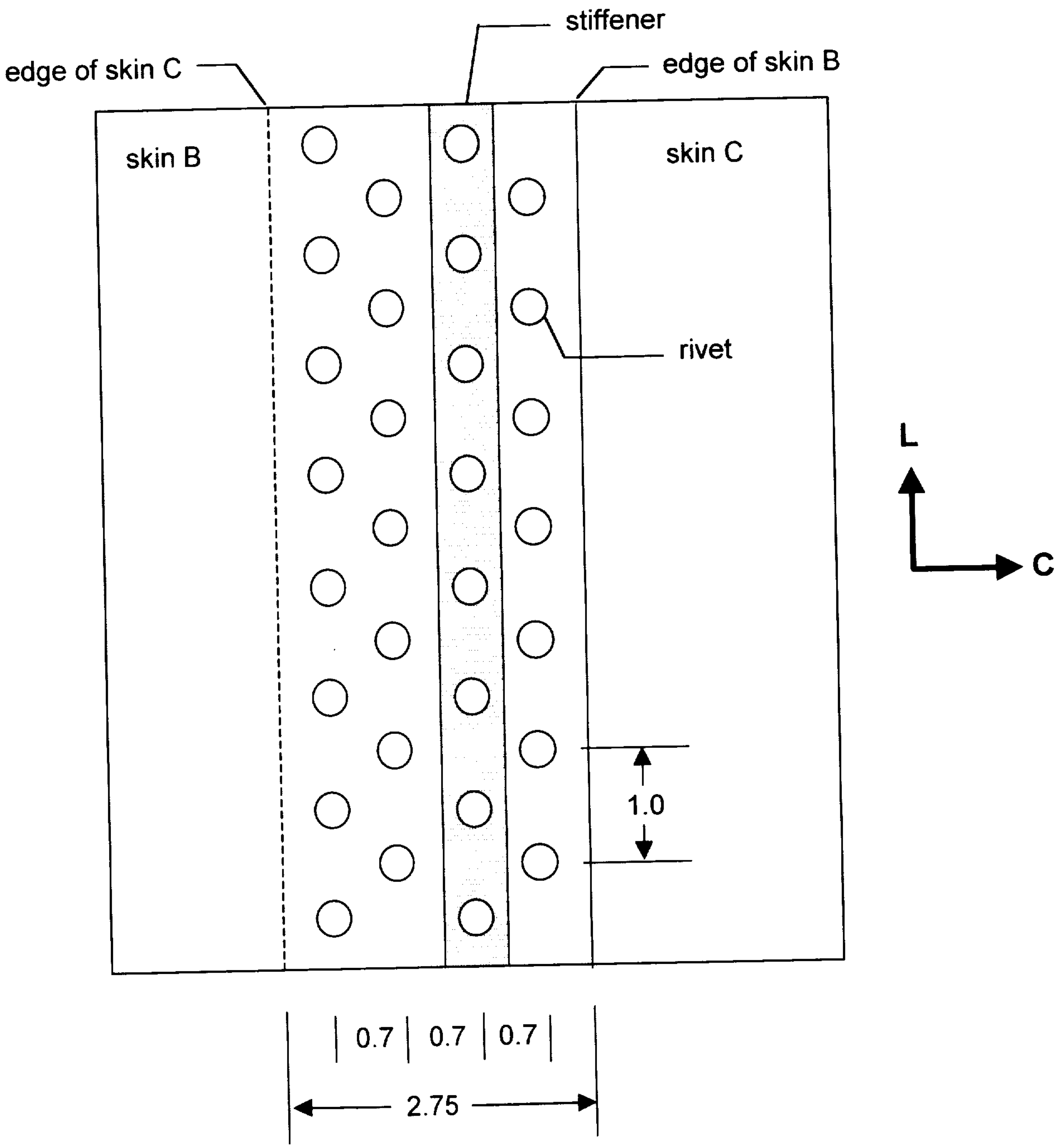

Figure 5. Schematic diagram of riveted splice joint with four rows of rivets. All dimensions are in inches.

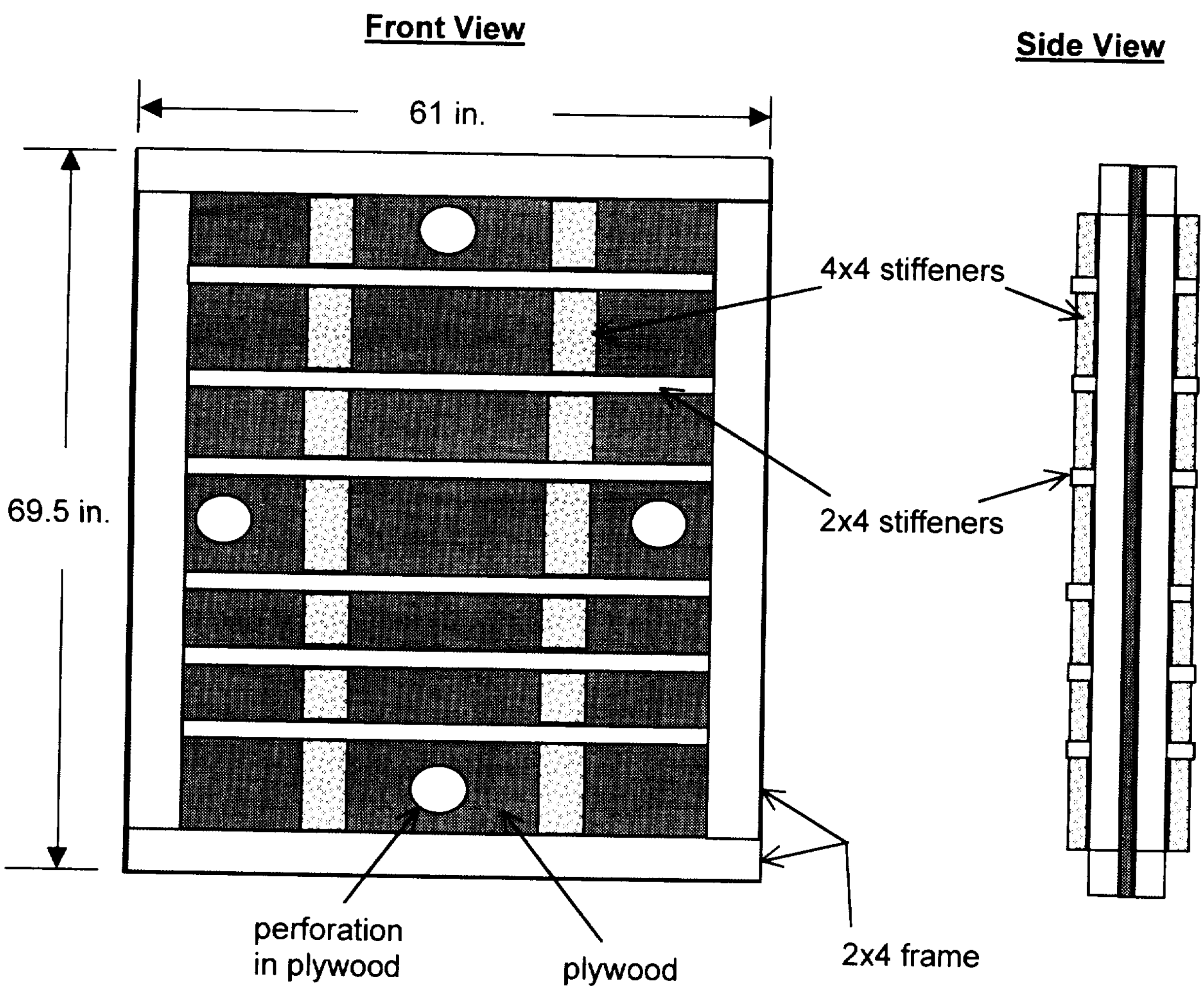

Figure 6a: Schematic diagram of support structure for panel pressurization test fixture. (Drawing is not to scale.)

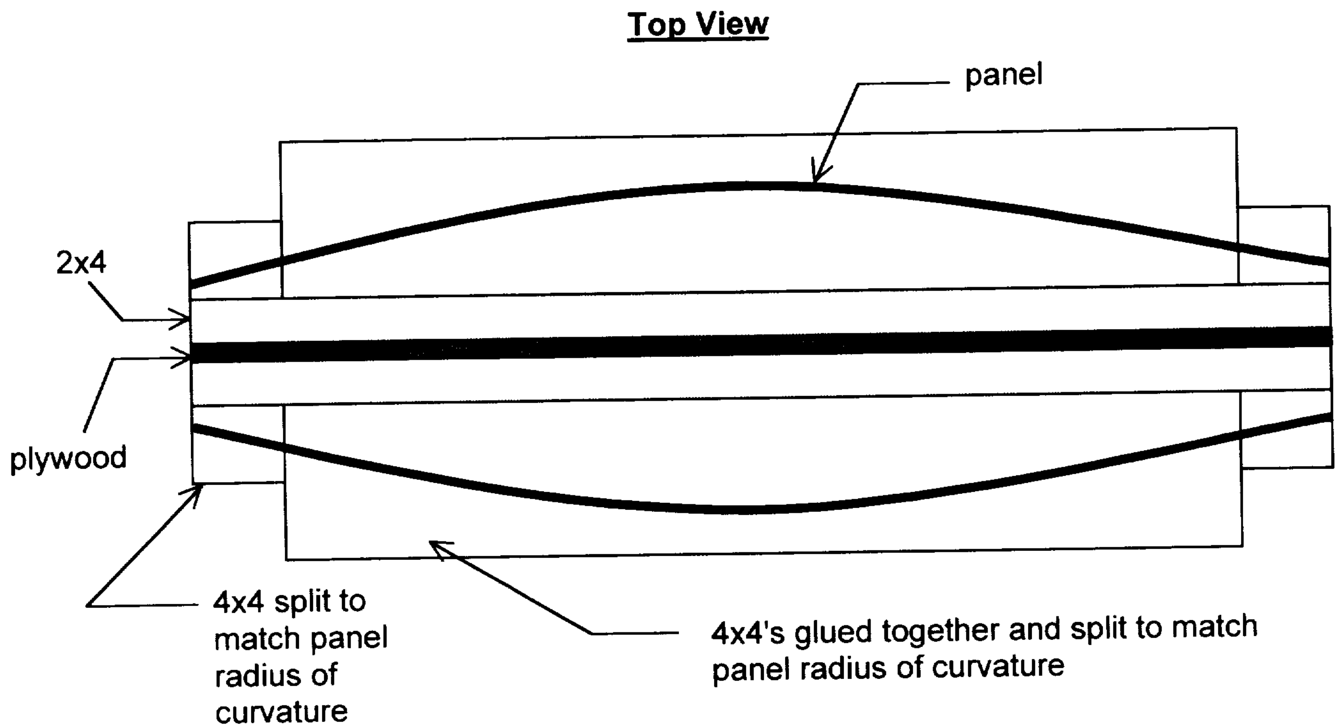

Figure 6b: Schematic diagram of clamping arrangement used to fasten fuselage panels to pressurization test fixture. (Drawing is not to scale.)

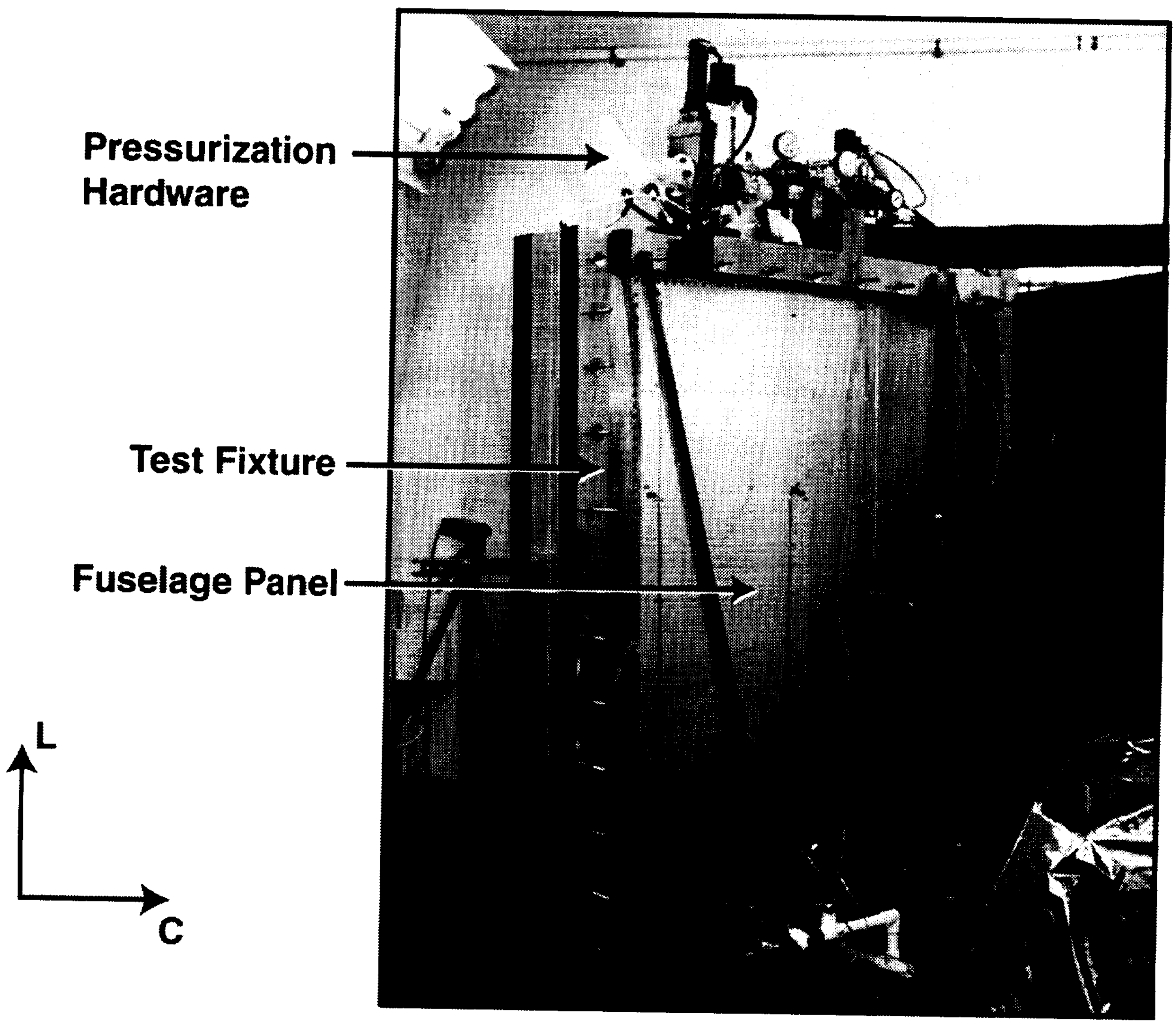

Figure 7. Fuselage panels mounted in pressurization test system at LaRC. (Second panel is hidden from view).

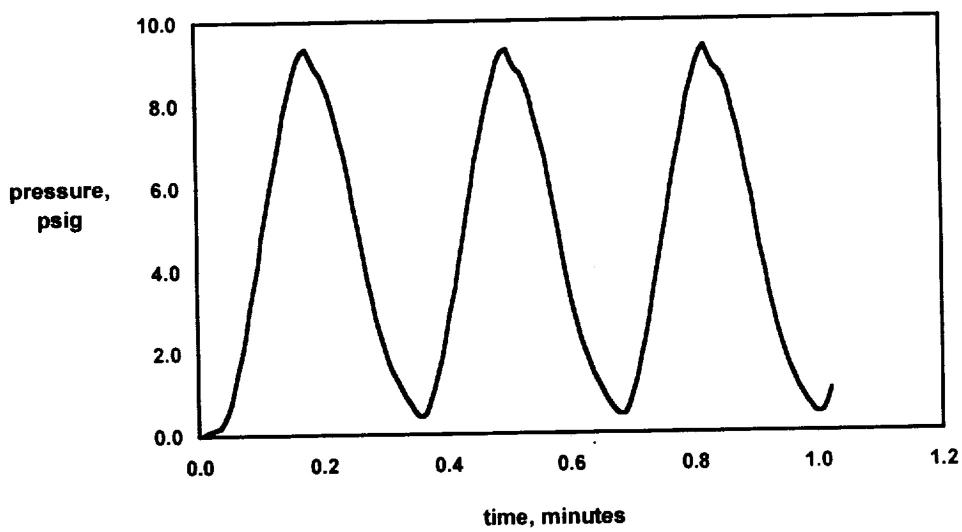

Figure 8. Representative pressure profile for fuselage panel pressurization fatigue test.

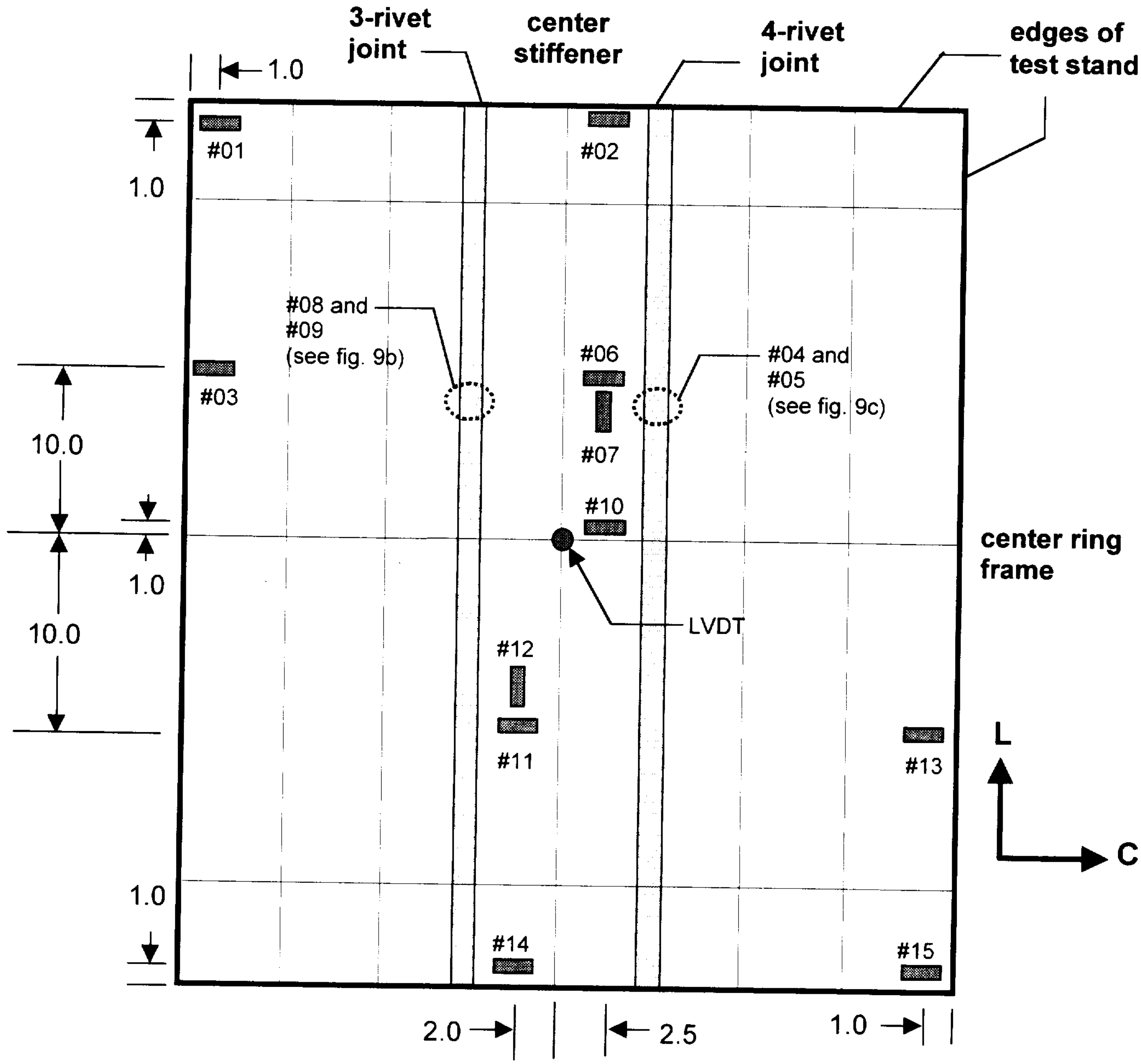

Figure 9a. Diagram of strain gage and LVDT locations on fuselage panels. All dimensions are in inches and drawing is not to scale. (Gages 04, 05, 08, and 09 were attached between rivets within the splice joints.)

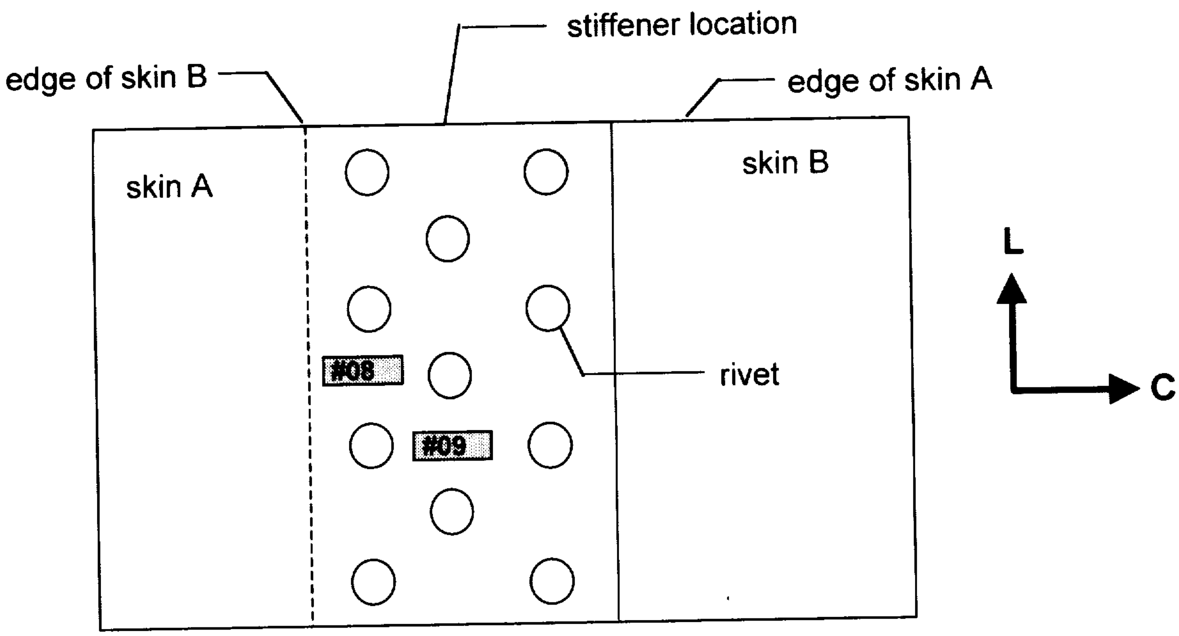

Figure 9b: Location of strain gages 04 and 05 in 3-rivet joint. (Both gages measure hoop strain.)

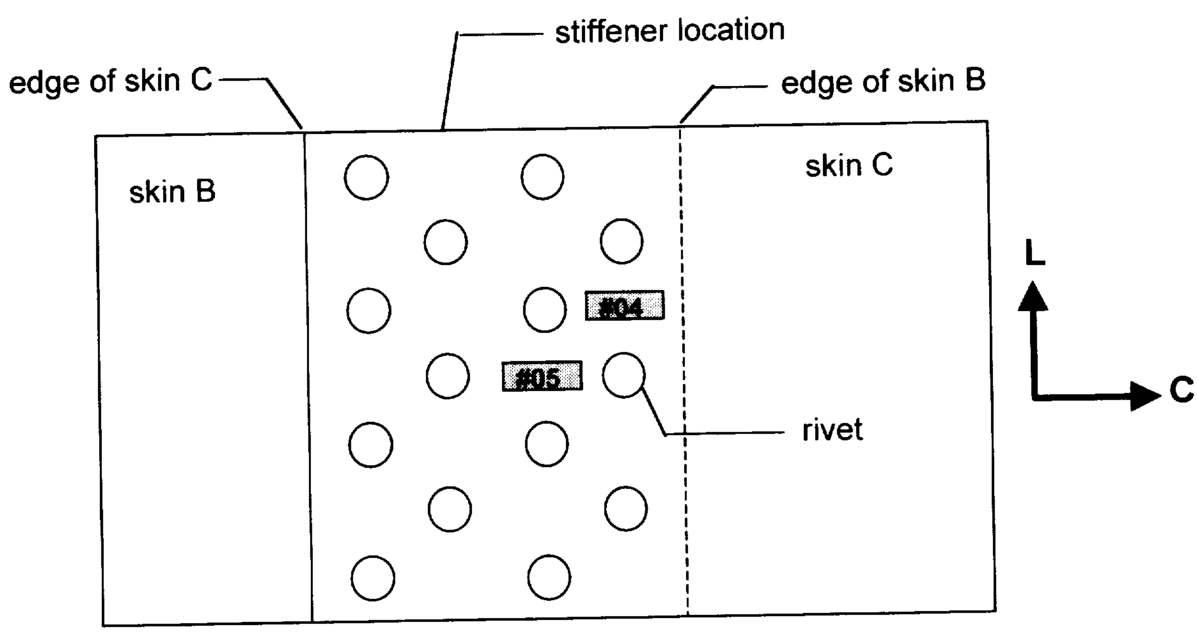

Figure 9c: Location of strain gages 04 and 05 in 4-rivet joint. (Both gages measure hoop strain.)

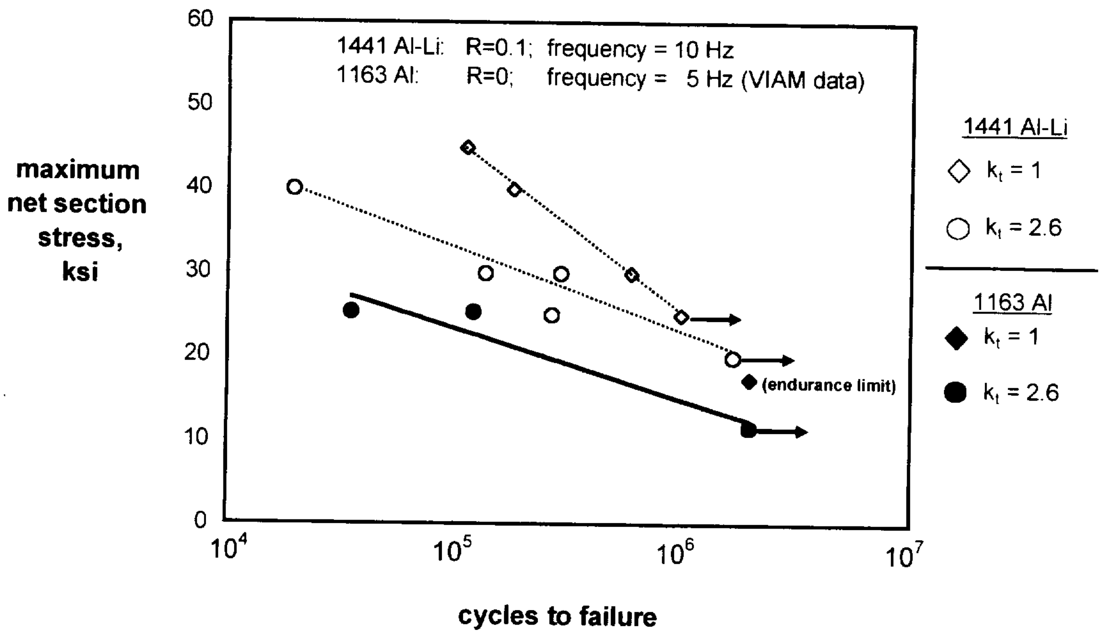

Figure 10: Fatigue behavior of 0.055-inch thick 1441 Al-Li sheet (longitudinal orientation).

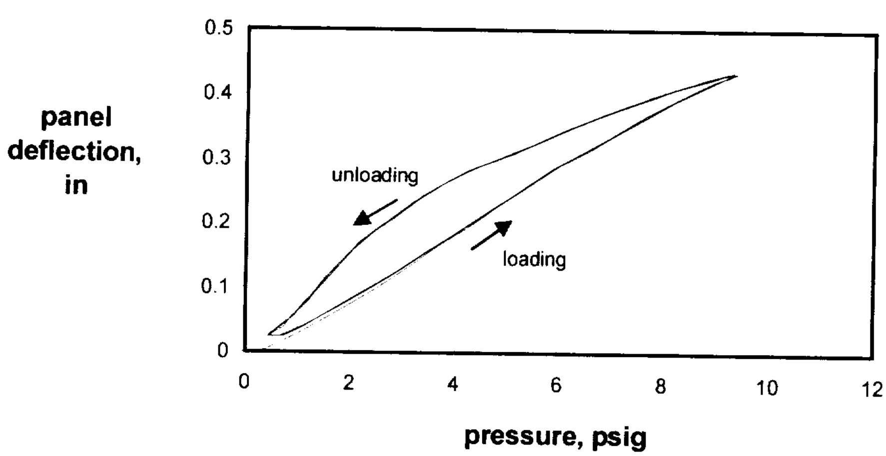

Figure 11: Fuselage panel deflection measured from LVDT. Three pressurization cycles are shown.

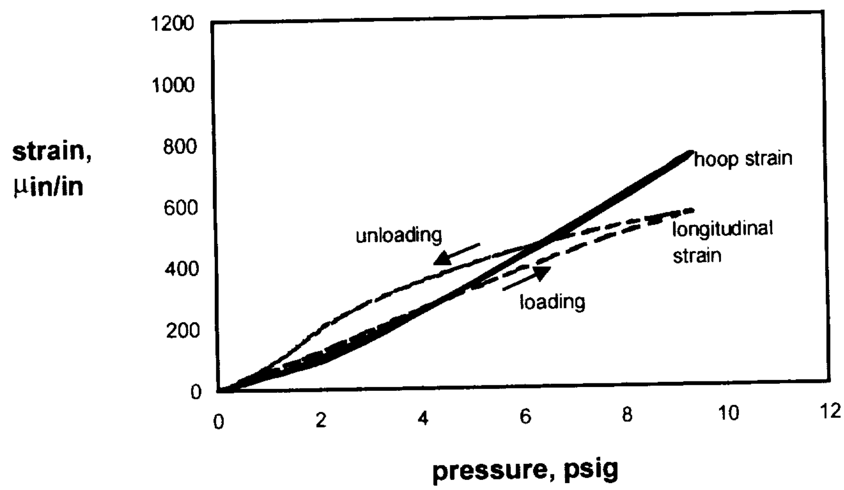

Figure 12. Fuselage skin strain response in the hoop and longitudinal directions. Three pressurization cycles are shown.

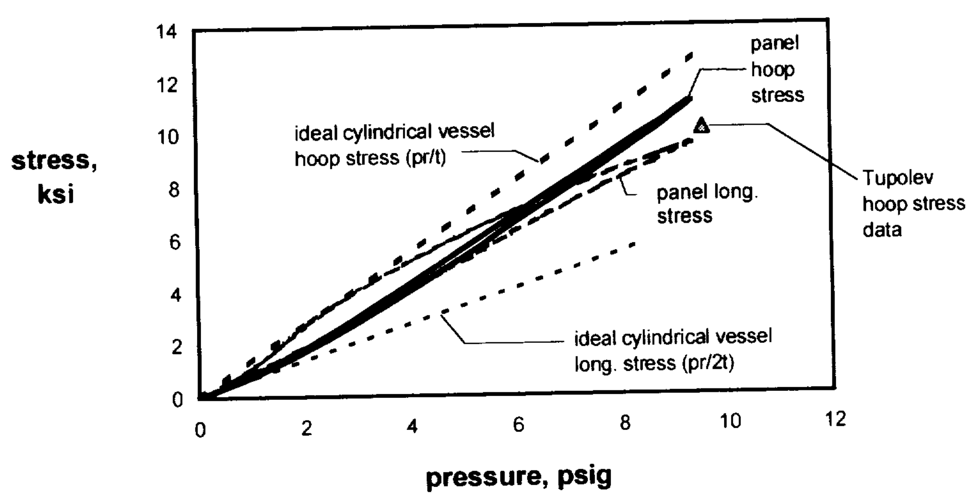

Figure 13. Fuselage skin stress response calculated from strain data. Three pressurization cycles are shown.

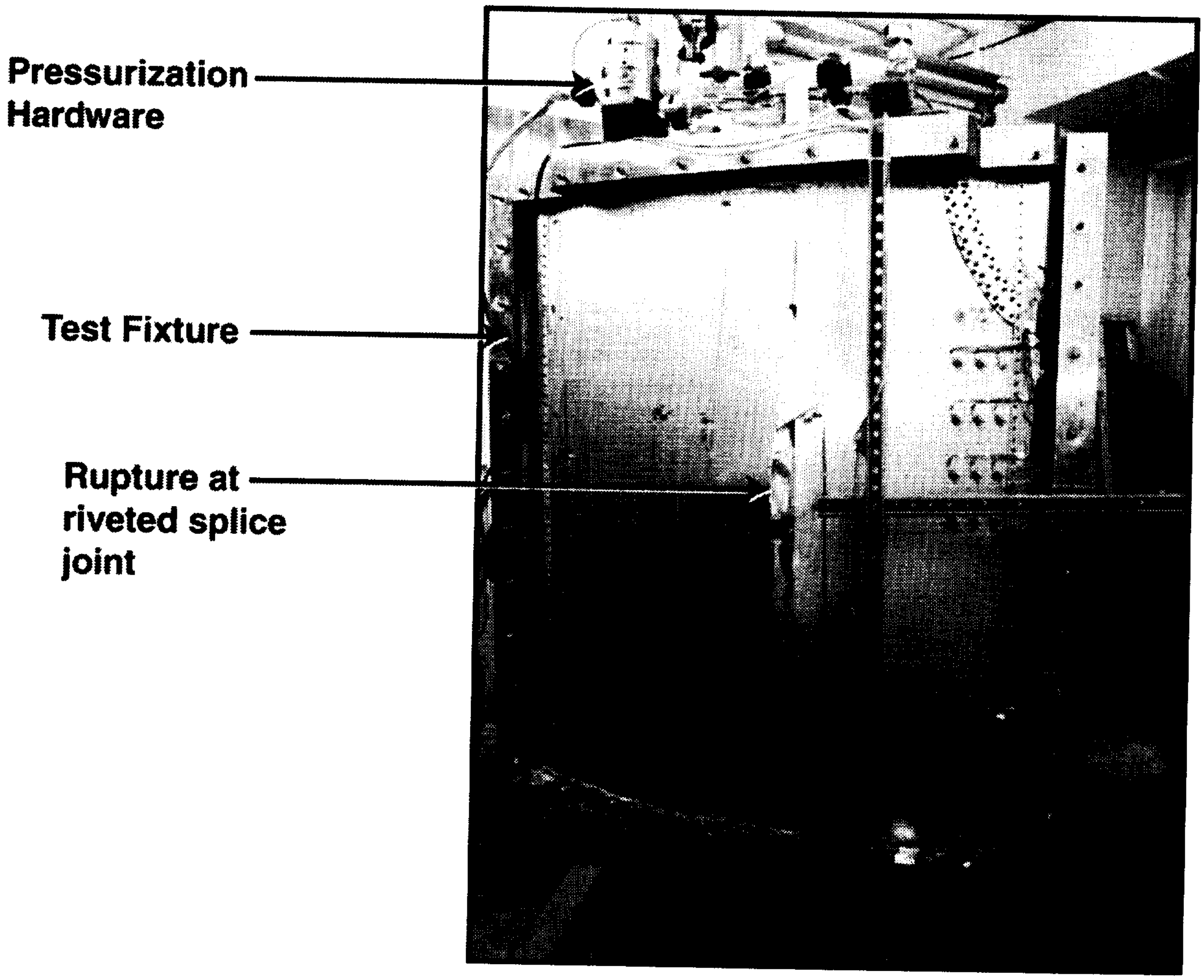

Figure 14. Ruptured fuselage panel (exterior view).

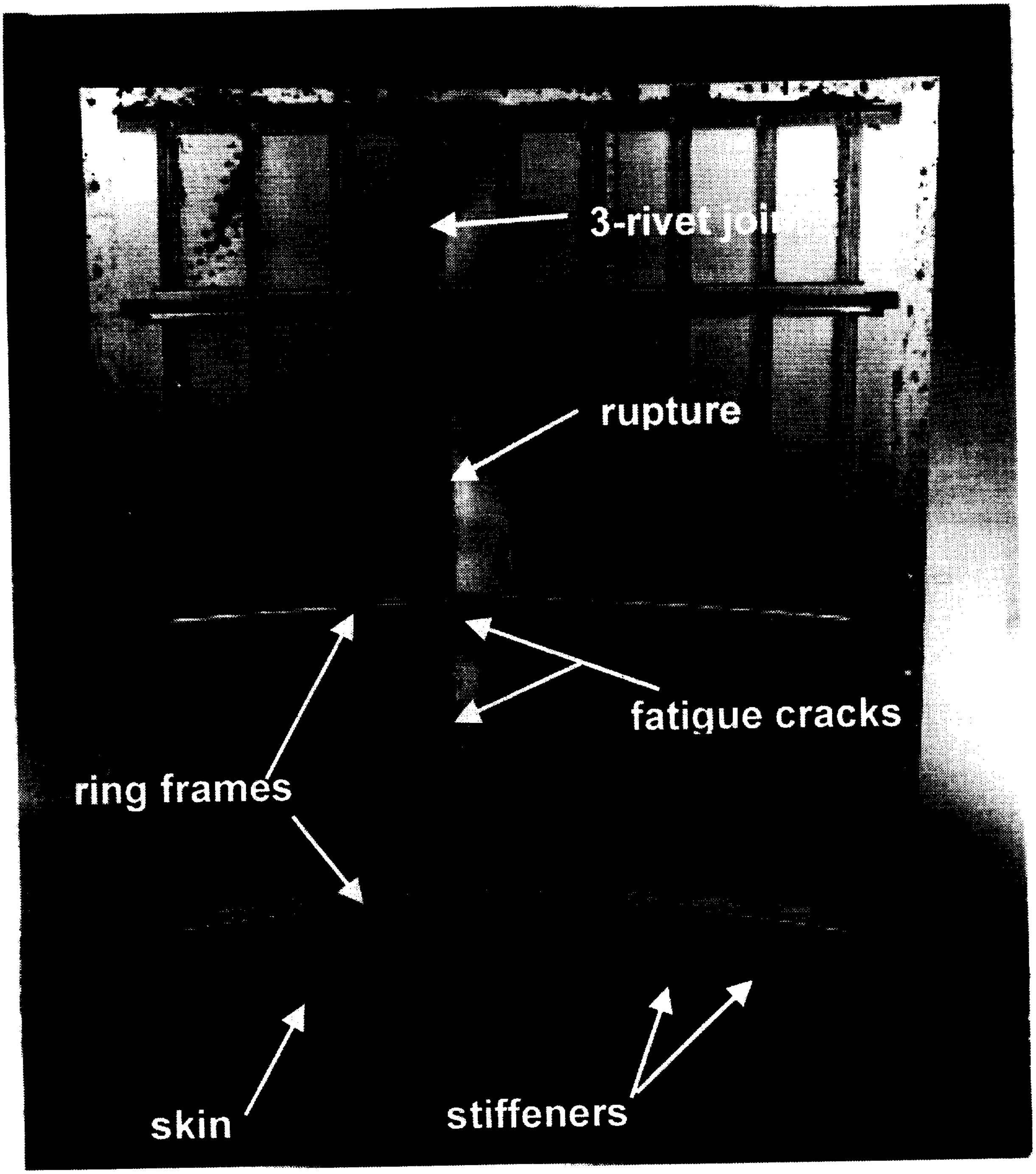

Figure 15: Ruptured fuselage panel (interior view).

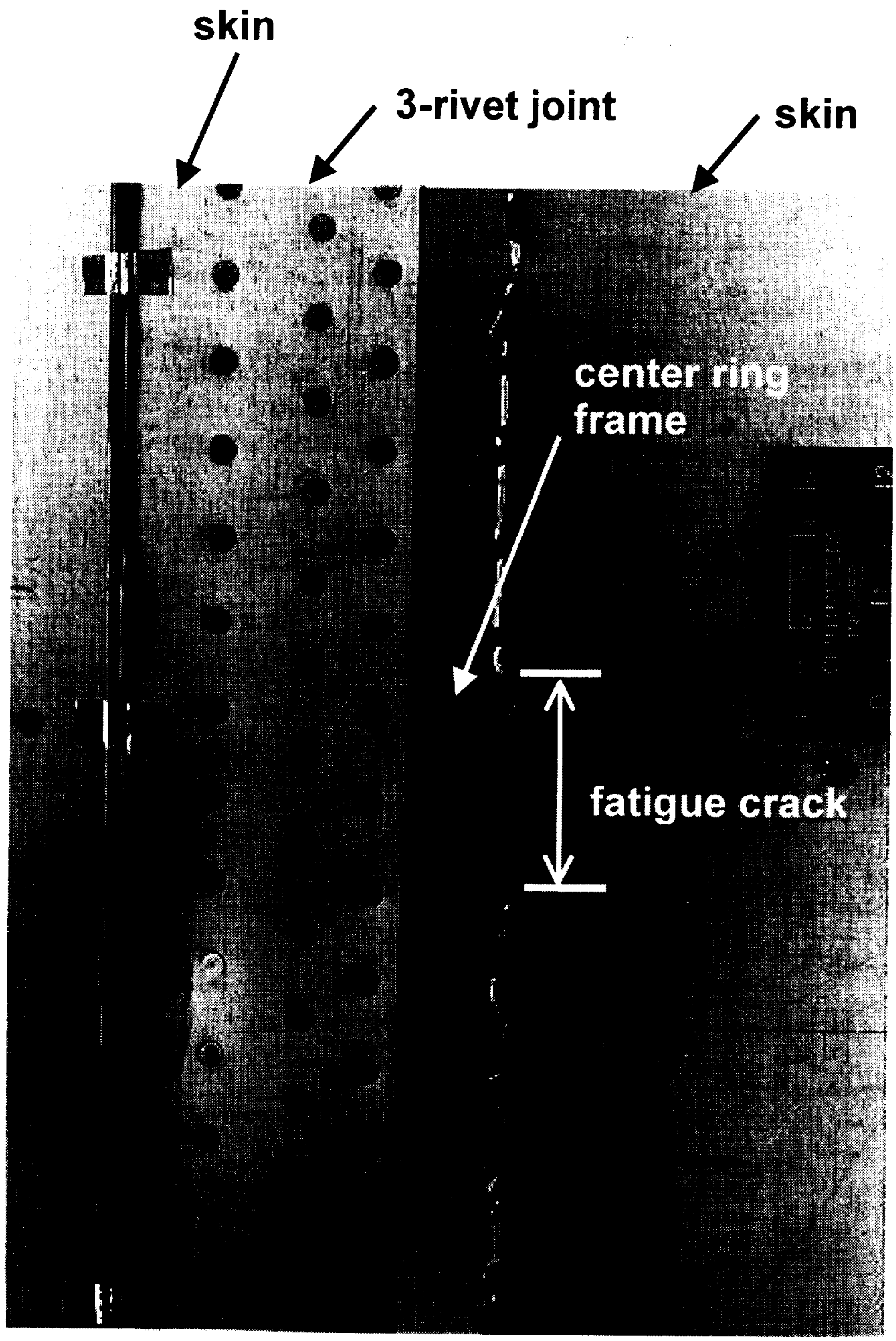

Figure 16: Detailed view of a fatigue crack in the ruptured fuselage panel (exterior view).

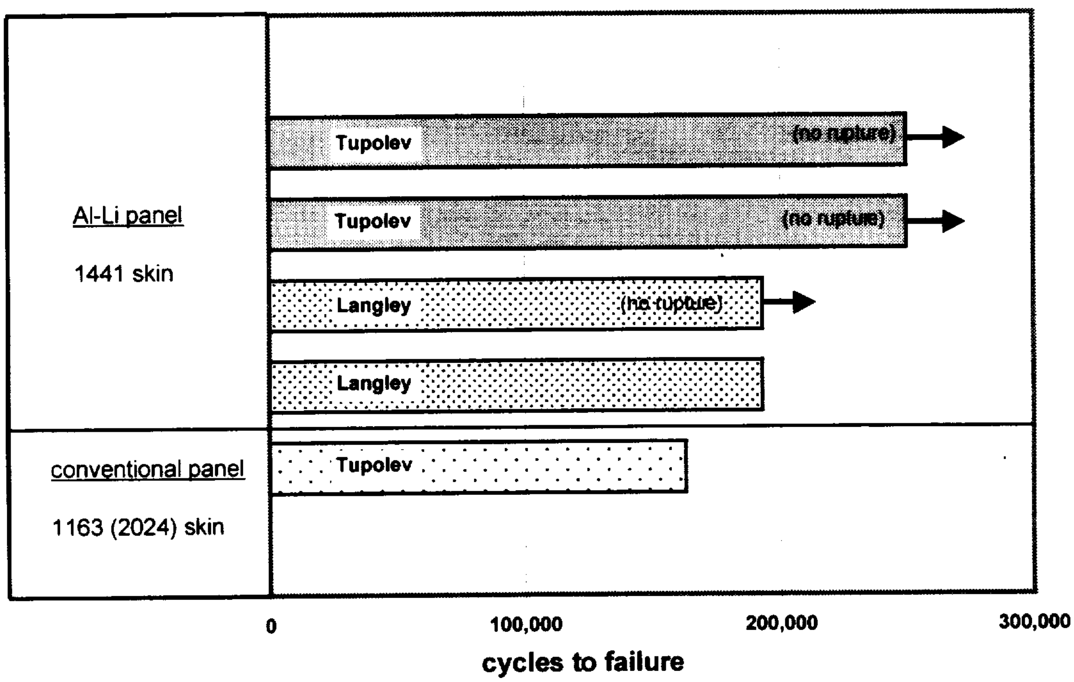

Figure 17. Pressurization fatigue life of Al-Li and conventional Tu-204 fuselage panels.

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4. TITLE AND SUBTITLE Evaluation of Pressurization Fatigue Life of 1441 Al-Li Fuselage Panel	5. FUNDING NUMBERS WU 522-18-48-02
6. AUTHOR(S) R. Keith Bird and Dennis L. Dicus	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) NASA Langley Research Center Hampton, VA 23681-2199	8. PERFORMING ORGANIZATION REPORT NUMBER L-17887
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001	10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA/TM-1999-209684

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
Unclassified-Unlimited Subject Category 26 Distribution: Standard Availability: NASA CASI (301) 621-0390	

13. ABSTRACT (Maximum 200 words)

A study was conducted to evaluate the pressurization fatigue life of fuselage panels with skins fabricated from 1441 Al-Li, an attractive new Russian alloy. The study indicated that 1441 Al-Li has several advantages over conventional aluminum fuselage skin alloy with respect to fatigue behavior. Smooth 1441 Al-Li sheet specimens exhibited a fatigue endurance limit similar to that for 1163 Al (Russian version of 2024 Al) sheet. Notched 1441 Al-Li sheet specimens exhibited greater fatigue strength and longer fatigue life than 1163 Al. In addition, Tu-204 fuselage panels fabricated by Tupolev Design Bureau using Al-Li skin and ring frames with riveted 7000-series aluminum stiffeners had longer pressurization fatigue lives than did panels constructed from conventional aluminum alloys. Taking into account the lower density of this alloy, the results suggest that 1441 Al-Li has the potential to improve fuselage performance while decreasing structural weight.

14. SUBJECT TERMS	15. NUMBER OF PAGES
Aluminum-lithium; Fatigue properties; Pressurization fatigue; Fuselage panels	27
	16. PRICE CODE A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL